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Research Article

Trade-offs and synergies in river-coastal restoration for the Ebro case (Spanish Mediterranean)

Agustín Sánchez-Arcilla[1], Luis Garrote[2], Vicente Gracia[1], Iván Cáceres[1], Xavier Sánchez-Artús[1], Nuno Caiola[3], Antoni Espanya[4], Manuel Espino[1], Miguel Ángel García[5], José María Grassa[6], Carles Ibáñez[3], David López[6], Marc Mestres[1], José Manuel de la Peña[6], Ernest Bladé[1], Umberto Pernice[7], Laura Puértolas[8], David Santillan[2], Shiri Zemah-Shamir[9], Ana Iglesias[2]

1 *Universitat Politècnica de Catalunya, Barcelona, Spain*
2 *Universidad Politécnica de Madrid, Madrid, Spain*
3 *Eurecat, Amposta, Spain*
4 *Generalitat de Catalunya, Barcelona, Spain*
5 *Confederación Hidrográfica del Ebro (CHE), Zaragoza, Spain*
6 *CEDEX, Madrid, Spain*
7 *Collaborative Innovation Management, Palermo, Italy*
8 *Albirem, Barcelona, Spain*
9 *Reichman University, Herzliya, Israel*
Corresponding author: Agustín Sánchez-Arcilla (agustin.arcilla@upc.edu)

Abstract

The paper tackles some of the major challenges associated with coastal risk reduction, based on restored river-delta-coast continuums. The presented approach builds on the Ebro River-Delta system, located in the Spanish Mediterranean coast, where available data and results from hands-on restoration actions provide quantitative evidence on the synergies and trade-offs when implementing restoration. The work addresses the evolution of climatic- and human-induced risks driven by recent deltaic evolution, starting in the 1960s, when socioeconomic development increased and river regulation by large dams in the lower river course started. Such development has driven up freshwater demand, consequently diminishing both liquid and solid discharges in the river system, which has affected the natural deltaic evolution, compounded by sea-level-rise and changes in storminess due to global warming.

Evolving erosion and flooding risks (problem symptoms) consider the decrease in sediment input to the delta and the increase in mean sea level (problem origin). To address the origin of the problem, we address sediment availability and transport in the lower river coast and reservoirs, followed by an assessment of sediment transport and deficit at the coastal fringe. The proposed solutions consider reservoir by-pass techniques, sediment mobilisation and downstream transport, as well as downstream transport capacity under present and future climates. Regarding the problem symptoms, we analyse the alternatives to enhance coastal resilience by means of restored coastal roughness resulting from embryonic dunes, lagoons and ridge and runnel topography. The analysis also considers coastal sediment recycling, based on a combination of wind and wave induced transports that provide a natural conveyor belt in dynamic equilibrium.

Finally, the paper systematises the main synergies and trade-offs that must be considered in any coastal restoration plan, targeting a low carbon reduction of coastal risks while maintaining the important socio-economic assets in the river-delta-coast system.

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The conclusion section briefly explores the extrapolation of the proposed approach to other vulnerable coastal regions in Europe.

Key words: Coastal roughness, coastal wetlands, Ebro Delta, restoration, river-coast connectivity, sediment recycling, Spanish Mediterranean

Introduction

A dynamic and connected river-delta-coast continuum provides a nature-based approach to enhance the resilience of regulated river floodplains and deltas. These systems increasingly suffer from erosion and subsidence due to the combined pressures of river regulation, coastal hardening and global warming (Sánchez-Arcilla et al. 2016; Moraes et al. 2022; van Rees et al. 2024). The Ebro Delta case, on the Spanish Mediterranean coast, is an illustrative example of how anthropogenic activities during the second half of last century have altered natural water and sediment flows and triggered cascading effects on the geomorphic, ecological and socio-economic equilibrium of the river-delta-coast continuum (Batalla et al. 2014; Caiola et al. 2014). These impacts are expected to increase under future climate scenarios due to accelerating sea-level-rise (IPCC 2021), increasing evapotranspiration and decreasing river run-off (López-Gómez 2022, 2024), while increasing risk levels for deltaic assets, often in conflict with upstream land, water and sediment uses.

The Ebro River-Delta-coast system is illustrative of vulnerable river-coast continuums under freshwater scarcity, high river regulation and fragmented governance, providing a small-scale test case for other deltas with more complicated geometries and more complex social and physical pressures, given the micro-tidal conditions at the coast and the limited permanent population (Day et al. 2019; Martin-Carrasco et al. 2025). The Ebro River Basin, located in the NE of the Iberian Peninsula, occupies a total area of 85,534 km^2 hosting more than 3 million inhabitants, where only 3% is unregulated, corresponding to an area of around 2,300 km^2, which has dramatically reduced the solid river discharge (Rovira et al. 2015), particularly its sand fraction. The resulting modification of water/sediment/nutrient fluxes has deeply affected the 320 km^2 of emerged deltaic area and adjacent shelf seas, which host unique habitats with rich biodiversity that critically depend on the Ebro discharges (e.g. Ibáñez et al. 2020a). Fundamental economic activities, including rice fields and aquaculture activities, have also been affected since river dams entered into operation in the 1960–1970 decade, resulting in coastal erosion rates up to 40 m per year in the river mouth area (e.g. Sánchez-Arcilla et al. 2016) that affect the local socio-economic context. These dynamics serve to illustrate the need for local restoration actions, which can be then upscaled to other deltas and low-lying coasts, testing the full range of adaptation solutions available under freshwater scarcity and high relative sea level rise rates, since subsidence is of the same order of magnitude as regional eustatic sea level rise.

These characteristics explain restoration barriers and enablers for this delta, which are well suited for larger and more populated deltas, where accommodation space may not be available. Restoration planning in such a context

requires a holistic approach, addressing land and water uses together with a consensus initial (reference) state of the system. This baseline is essential to assess future states and, in the case of the Ebro, would correspond at least to the river flow conditions before the 1960–1970 decade, representing the conditions prior to the construction of the main dams in the lower basin. Restoration targets must also contemplate recent (2000 to 2020 interval) and future (2030, 2050 and 2100 horizons) conditions, making the restoration compatible with river basin and coastal management/protection plans for the Ebro River and Spanish coast, which usually address two horizons (2045 and 2100) and two future climate scenarios (SSP2-4.5 and SSP5-8.5). SSP2-4.5 is a "middle-of-the-road" scenario, with a global temperature rise of 2.7 °C by the end of the century and without notable shifts in socioeconomic factors. SSP5-8.5 is a pessimistic scenario to be avoided, with a global temperature rise of 4.4 °C or higher by 2100 and a rapid economic growth, based on fossil fuels and energy-intensive lifestyles (IPCC 2021). Framed by these plans, the target status of the Ebro Delta is being delineated by ongoing discussions across co-management tables, considering different stakeholder expectations and natural resource (freshwater and sand) availability, while engaging river/coast authorities, central/regional relevant departments and a large number of municipalities, environmentalist groups and other interested parties.

These discussions have identified a number of synergies and trade-offs for the shared benefits from a systemic river-coast restoration, which vary with stakeholder positioning and that will evolve with time, depending on climatic/management scenarios and natural resource availability. Global warming is associated with increasing freshwater scarcity and land-use changes in Mediterranean basins (Hassoun et al. 2024), which requires the maintenance of minimum environmental flows (established at 80–100 m^3/sec for the lower Ebro River) and a coordinated engagement of stakeholders, supported by a negotiation process that considers different and conflicting gains and pains. Such water scarcity also affects the feasibility of controlled floods, essential for enhancing downstream sediment transport capacity, since the sand fraction is mostly transported as bed-load and depends on river flows exceeding 500 m^3/sec, well above the environmental flow. The implication is that deltaic sustainability and river environmental quality compete for a scarce resource, where demand exceeds availability, leading to an imbalance that is projected to grow under future climate and management scenarios (longer drought periods, river diversions etc.). Nevertheless, environmental flows are in Spain, by law, a restriction to human water uses, meaning that there is a legal guarantee to sustain the established environmental flow regime.

The current river regulation, with 187 dams, has reduced the total solid discharge by more than 90% and almost100% for the sand fraction (Ibáñez et al. 2020a, b). As a result, sand delivery to the delta is extremely limited, estimated to be about 30,000 m^3/yr with an interval of variation between 12,000 and 48,000 m^3/yr (CEPYC 2021). Furthermore, this solid discharge goes mainly to the northern part of the delta, resulting in a growing sediment starvation for the southern hemi-delta, which receives only about 1,500 m^3/yr of sand. The scarcity of sand and freshwater imposes constraints on river-coast restoration strategies, leading from one side to trade-offs which may hamper restoration decisions (e.g. additional accommodation space), but from the other side, to

synergies associated with stakeholders' co-benefits that can suggest preferred options. The sediment retained in the reservoirs has created new wetlands at the reservoirs' tail and these newly-created environments hinder the survival of deltaic wetlands, illustrating another trade-off under sediment scarcity, between habitats at two different locations along the river-delta continuum. Synergies can be illustrated by the new approach to coastal restoration, featuring maximised durations for limited-volume sand nourishments. This is accomplished by reconstructing embryo dunes that counter the alongshore sediment transport rate (Sánchez-Arcilla et al. 2023) and, therefore, are in synergy, under sediment and freshwater scarcity, with limited river discharges when compared to historical sediment supplies during the last two centuries (Xing et al. 2014). Trade-offs are mainly related to the scarcity of natural resources for which there is competition amongst stakeholders, projected to aggravate under global warming with higher evapotranspiration and irrigation needs. Synergies are related to the shared benefits from controlled floods (improving river habitats and supporting deltaic resilience) and nature-based restoration of the river-coast continuum. The restoration synergies can be illustrated by sediment coming back to the now armoured river bed, longer lasting coastal nourishments and restored habitats such as coastal wetlands, which, through the provisioning of ecosystem services, reduce risks and enhance blue carbon.

This paper presents and discusses a suite of innovative restoration alternatives for the Ebro system, many of which are being tested through pilot actions. These alternatives, framed by natural resource scarcity and Mediterranean climate variability (illustrated by droughts and impulsive storms), promote synergies, aiming to spread costs and impacts across stakeholders, exemplified by the need to share river-born sediments between deltaic plain and coastal fringe, where only sand or coarser fractions are stable in the latter. These restoration actions, involving a level of innovation, require joint monitoring of the river-delta-coast system, controlling the actual water-sediment fluxes and the delivery of ecosystem services. This holistic monitoring (river, deltaic and coastal domains, combining key hydro-morpho-eco variables) should lead to reduced environmental impacts and enhanced sediment recycling (from reservoirs to the delta and along the deltaic coast). Restoration will improve the good environmental status of the river-delta-coast continuum, based on connectivity, natural dynamics and the delivery of services from healthy ecosystems, supported by synergies that maximise the resilience of river and coastal environments. Morphodynamic synergies are linked to an innovative approach to coastal nourishment that maximises coastal roughness (for risk reduction), recycles available coastal sand (Sánchez-Arcilla et al. 2024) and enhances resilience for the sandy coastal fringe until river-to-coast connectivity has been properly restored and sufficient sand volumes arrive to the delta. The restoration plan proposed here considers the main coastal sink areas, located at the northern and southern bays, where yearly sediment deposition ranges between 9,000 m^3 and 23,000 m^3 (CEPYC 2021). Additional sink areas can be found in the lee side of the southern barrier beach (associated with over-wash) and in submerged prodeltas (relict sedimentary deposits corresponding to old river mouths). Using prodeltas as a source for artificial coastal nourishment illustrates the trade-off between consuming a "fossil" and limited sedimentary resource to protect present coastal assets versus the potential destabilisation of the deltaic profile

under larger waves (greater depths in the dredged areas) and enhancing deltaic coast erosion due to the loss of protection offered by the submerged prodeltas. The enhanced solid river transport due to improved connectivity along the river illustrates the synergy when sharing, such a sedimentary input between the northern and southern hemi-deltas, while the riverine sand input under present conditions goes mainly (about 95%) to the northern part of the delta and only 5% to the southern part of the delta, with a significantly longer coastline to nourish.

River and coastal restoration needs

Problem setting

Anthropogenic activities in recent decades, such as dam construction, irrigation, canalisation and land-use changes, have altered natural fluxes (water, sediments and nutrients) along the Ebro River, triggering cascading effects on the ecologic and geomorphic equilibrium of the river-delta-coast continuum (Caiola et al. 2014; CEPYC 2021; Sánchez-Arcilla et al. 2023). The consequences of these alterations are multiple and impact ecosystem health and socioeconomic activities due to reduced water and sediment delivery to the Ebro Delta (Fig. 1), which increases coastal vulnerability (linked to erosion and flooding) under relative sea level rise and changes in storm surges and waves (Sierra et al. 2020, 2023). Understanding the complex hydro-morpho-dynamics of the Ebro system and their response to restoration interventions is essential for providing information for adaptive management strategies and assessing potential improvements in the system's natural resilience.

The Ebro Basin, in addition to supplying the population with freshwater, supports numerous socioeconomic activities: agriculture, farming, hydropower generation, power plant refrigeration, tourism and associated industries. Today, the lower Ebro River is regulated by three reservoirs: a) Mequinenza Reservoir, with a storage capacity of 1,500 hm^3 (now 1,373 hm^3) and regulating the Ebro flow; b) Ribarroja Reservoir, with a capacity of 210 hm^3 (now 152.9 hm^3) and regulating the flow of the Cinca and Segre Rivers (tributaries of the Ebro); c) Flix

Figure 1. The Ebro River catchment basin in Spain (left, own elaboration), with the regulated (in blue) and unregulated (in red) parts and the Ebro Delta (right, Sentinel image), showing the surface plume with solid suspended material during controlled floods.

Reservoir, relatively smaller with 11 hm^3 and located downstream of the previous ones, about 100 km upstream of the river mouth. These reservoirs produce significant benefits to many stakeholders, being initially built for hydropower generation with 630 MW of total installed capacity, which guarantees a strategic energy production for the national grid. Moreover, the reservoir system regulates the flow for cooling the downstream Ascó nuclear power plant, which acts as a safety support for situations with loss of external electricity supply or the need to restore a zero voltage in the network (Ribarroja hydroelectric power plant). In addition, the system of Mequinenza-Ribarroja-Flix Reservoirs provides a guaranteed water supply to a diversity of users that abstract water from the reservoirs and the lower Ebro River, including the rice fields in the delta. These reservoirs are currently operated to sustain a flow set at 100 m^3/s through the Ebro River mouth, which is about 20% of the estimated mean flow in the natural regime. Ideally, environmental flows should reach approximately 315 m^3/s, with specific targets of 227 m^3/s during dry years, 302 m^3/s in average years and 398 m^3/s in wet years (Caiola et al. 2014). The flow regulation provided by the reservoirs has practically eliminated the flooding risk in the lower section of the Ebro River, where the reservoirs have contributed to develop water-based environmental and recreational activities, as well as the current socioeconomic development of the lower river and delta. One of the trade-offs is the reduction of solid river discharges, which has modified the sedimentary balance in the lower Ebro due to river regulation, dam barrier effects and land/water uses in the upstream catchment basin.

This Delta has experienced intense reshaping and subsidence since the 1960s, with local peak erosion rates up to 40 m/year (Sánchez-Arcilla et al. 2008; Sánchez-Arcilla et al. 2016) and relative Sea Level Rise (SLR) exceeding 5 mm/year (Grases et al. 2020; Rodríguez-Santalla and Navarro 2021). Due to the regulation of the Ebro River and competing freshwater uses, the deltaic coast evolution is now controlled by incident wave energy and storm surges that may go up to 0.5 m in this coast, resulting in growing risks under future climate and management scenarios when combined with accelerated SLR rates (Genua-Olmedo et al. 2016; Sánchez-Arcilla et al. 2022). The Ebro Delta features (Fig. 1) about 320 km^2 of emerged area and 50 km of coastline, with circa 50,000 inhabitants and is one of the main deltas in the Mediterranean, constituting a microtidal sediment-starved deltaic system. It hosts unique habitats with a rich biodiversity and important socioeconomic activities, such as rice fields or aquaculture, which depend on the Ebro River discharges (Ibáñez et al. 2020a) for survival.

The main restoration goal is to recover a connected and, therefore, resilient (Sánchez-Arcilla et al. 2022) river-delta-coast system, where a sufficiently wide and morphodynamically rough coast maximises the duration of artificially supplied sand, waiting for an additional solid discharge from the river which will have to be carefully regulated to maintain risk levels within acceptable bounds during this century. In the performed analyses, we compare the river-delta-coast system under: a) pre-dam conditions (until 1970); b) evolving historical conditions (1970 until 2024); and c) future scenarios (until the end of this century). The proposed restoration considers the limits of conventional coastal engineering (both hard groynes and soft nourishment) and the need to apply whenever possible nature-based solutions, with a reduced carbon footprint and enough flexibility to become more resilient under future climate scenarios.

Lower river course and reservoirs: sediment availability and transport capacity

Sediment dynamics in the lower Ebro River course has been extensively studied and is well characterised, including the effects of flow alteration by the construction of reservoirs and subsequent river regulation (Flumen Institute 2022, 2024; CHE 2023). Reservoir construction occurred mainly in the twentieth century, when more than 7,000 hm^3 of reservoir storage was developed, of which more than 4,000 hm^3 entered into operation in the 1955–1965 decade, including the Mequinenza Reservoir, the largest one in the Basin with more than 1,500 hm^3 of storage capacity. Data on the mean annual sediment transport prior to reservoir construction is limited, but it has been estimated (Ibáñez et al. 1996) as slightly below 30 Mt/yr, based on data compiled by Gorría in 1877. This amount is in stark contrast with estimates between 2 Mt/yr and 3 Mt/yr for the 1962–1963 period, where there was already a significant reservoir capacity in the Basin (Catalán 1969) or with the more recent estimate for the 1990–2010 decade (CEPYC 2021; Sánchez-Arcilla et al. 2023) which was below 0.1 Mt/yr. There have been several recent field campaigns to assess downstream sediment transport, either through direct measurements (Vericat and Batalla 2006; Batalla and Vericat 2011; Batalla et al. 2014; Rovira et al. 2015), through turbidity estimates (Tena et al. 2011; Tena et al. 2012) or models (Xing et al. 2014). Recent campaigns apply a methodology and instrumentation that consider spatial representativeness and duration effects, enhancing the reliability of the resulting data. From the registered data, the sediment flow upstream of the Mequinenza Reservoir has been estimated within the range 0.6 Mt/yr and 1.6 Mt/yr, while the estimate after the Ribarroja Reservoir shows a steady decrease over time, going from 0.4 Mt/yr in the last years of the past century, to 0.1 Mt/yr derived from the most recent campaigns in this century. The amount of solid river discharge appears to grow downstream, because a significant part of the sediment bed-load transport towards the mouth comes from the contribution of tributaries downstream of the reservoirs, since, further upstream, the bed is armoured by the natural washing of finer sediments. Near the mouth, the uncertainty is larger due to complex interactions with the salt wedge (Sierra et al. 2004), the barrier effect of the river mouth bar (Grifoll et al. 2024) and the control exerted by a changing sea level (e.g. storm surges simultaneous to higher natural discharges due to intense precipitation associated with local storms). All of these are conditioned by the sharp decrease in solid river transport, particularly for the sand fraction.

The controlled releases of water with a low sediment load from the reservoirs modifies the river morphology, leading to incision of the river channel and altering channel morphology with bank erosion. The sediment remaining on the river-bed is flushed downstream by such comparatively higher flows, leading to a progressive degradation and armouring of the river-bed, whose armour layer is broken and re-established during flood events, as recorded in the 2002–2004 period (Vericat and Batalla 2006). During these field campaigns, river-bed sediment was sampled on several exposed bars with sparse vegetation and bed-load samples were taken during high flows. The transition from armoured beds (low flow rates) to incisions (high flow rates), where the armouring was destroyed and the bed material dragged, was also monitored.

Sediment accumulation in reservoirs

Sediment transport in the Mequinenza Reservoir has been assessed through multiple bathymetric surveys (1961, 1982, 2012 and 2022), along with broader studies of sediment accumulation. According to a national screening by CEDEX (Avendaño Salas et al. 1997), Mequinenza had lost an estimated 92.8 hm^3 of capacity by 1982, 16 years after its commissioning, implying an average sedimentation rate of 5.8 hm^3/year. Later, the Ebro River Basin Authority carried out field surveys during 2011–2012, capitalising on historically low water levels that allowed detailed cross-sectional comparisons with original dam cartography. This analysis, limited to the final 35 km of the Reservoir, revealed 4.91 hm^3 of accumulated sediment. Broader estimates across the entire Reservoir provided sediment volumes of 133 hm^3 in 2008 and 76.9 hm^3 in 2011, leading to a reconciled range of total sediment accumulation between 75 hm^3 and 100 hm^3. This suggests a long-term average annual sedimentation rate of approximately 1.5–2 hm^3/year since its construction in 1964. Sediment trapping efficiency is estimated to be near 100%, attributed to the Reservoir's large size and over–100 km length. Recent assessments (Flumen Institute 2022, 2024) estimate the total sediment mass accumulated to be 422.7 Mt.

For Ribarroja Reservoir, the bathymetric surveys, conducted in 1967, 1982 and twice in 2007, have been used to quantify sediment accumulation. The CEDEX report estimated a capacity loss of 12.24 hm^3 by 1982, 13 years after dam operation began, implying an average annual sedimentation rate of 0.94 hm^3/year. Further, using surveys conducted between 1997 and 1999, some recent studies (Dolz et al. 2009, 2010) estimated that sediment volume had reached 13.1 hm^3 by 2007, reflecting a lower average deposition rate of 0.34 hm^3/year since 1968. The sediment trapping efficiency in Ribarroja is significantly lower than Mequinenza's, estimated at around 40%, due to its smaller storage volume and shorter retention time. The most recent mass-based accumulation estimates place the total sediment volume at 65.2 Mt (Flumen Institute 2022, 2024).

Across these studies, Mequinenza shows a wide range of estimated sedimentation rates: from 5.8 hm^3/year in early years to a long-term average of 1.5–2 hm^3/year, with total sediment volumes ranging from 75 to 133 hm^3 (or 422.7 Mt by mass). Ribarroja shows a more modest, but consistent sedimentation pattern, with rates decreasing from 0.94 to 0.34 hm^3/year and an estimated total volume of 13.1 hm^3 (or 65.2 Mt). These variations reflect differences in reservoir design and sediment trapping efficiency, which, summarising the presented results, is nearly 100% in Mequinenza versus around 40% in Ribarroja.

Rate of subsidence within the deltaic body

The Ebro Delta, located near the boundary between the Iberian and Mediterranean Sea plates, experiences slow tectonic subsidence and comparatively faster subsidence due to compaction and reduction of sedimentary supplies (e.g. Rodriguez-Lloveras et al. 2020). This reduction comes from sediment trapping in the reservoirs, water abstraction due to irrigation and other uses and limited overbank flooding, which has affected the deltaic vertical sediment balance. Historically, the Delta was maintained by periodic river-borne sediment deposition, associated with overbank and marine sand flooding under high discharges and

storm events. Both have been hindered in the last decades, which has enhanced subsidence, as there is no new material to counterbalance natural subsidence.

Studies conducted using Differential Interferometry Synthetic Aperture Radar (DInSAR), have provided estimates of subsidence around 1–2.3 mm/y in the central and northern parts of the Delta (Rodriguez-Lloveras et al. 2020), although data showed spatial dispersion, where areas with groundwater extraction or prevented flooding show higher rates of subsidence. Further data on this process have been derived from precise topographic levelling itineraries, based on three fixed topographical reference starting measurements from 1927: one outside the Delta, one in the middle of the Delta (near the island of Gracia) and one near the river mouth. In 2012, two precision levelling campaigns were carried out along the same lines measured in 1927, but also including several itineraries crossing the Delta in different directions, with more than 200 survey points that were left on site. A new high-precision study was carried out in 2021, following the same itineraries of 2012 (CHE 2023), to analyse and compare elevation changes over a 9-year period. Results show a dispersion of subsidence rates, associated with the inherent limitations of in-situ observation and analysis techniques, surveyed period and authors, with averaged values of a few millimetres per year (1 to 3 mm in Rodriguez-Lloveras et al. 2020) and significant standard deviations (e.g. 8–10 mm from the 1927 to 2012 comparison). In spite of these limitations, subsidence characterisation is essential to assess deltaic erosion and flooding risks and should, thus, be included in future restoration solutions, using the best available combination of in-situ and satellite data for increasingly reliable estimations.

Coastal fringe: sediment transport and deficit

The deltaic 3D geometry has been evolving during the last decades towards a plan shape more in equilibrium with incoming wave energy and acting sea levels, integrating storm variability, decreasing riverine inputs and relative-sea-level-rise (RSLR). The result (Gracia et al. 1998; Sánchez-Arcilla et al. 2008; CEPYC 2021) has been a smoothed bathymetry and coastline, more parallel to incident wave crests and in dynamic equilibrium with prevailing wave and surge conditions (Fig. 2). Once the reservoirs were built, there was a phase of rapid coastal erosion in the first 25 years (1966–1990), which was especially acute in Cape Tortosa with a 2 km setback (Sánchez-Arcilla et al. 2008). Such reshaping has led to a more rounded shoreline that reduces long-shore transport rates (Sánchez-Arcilla et al. 2016). The coastal evolution has slowed and is characterised by a nearly closed sand budget, with widespread erosion and localised deposition mainly at the apex of the two spits. Shoreline evolution during the last 50 years is characterised by a well-defined, at least qualitatively, along-shore sediment transport pattern (Fig. 3), with average transport rates defined by an average value together with an interval of variation derived by CEDEX from analyses that consider transport formulations and aerial shoreline images. These along-shore sediment transport estimates are bounded by potential transport values, with verified rates falling within the proposed intervals and conditioned by sediment availability, RSLR and wave climate (Sánchez-Arcilla et al. 2016, 2021; CEPYC 2021).

Sediment transport estimations are based on three complementary approaches (Sánchez-Arcilla et al. 2023) and have been checked with a locally

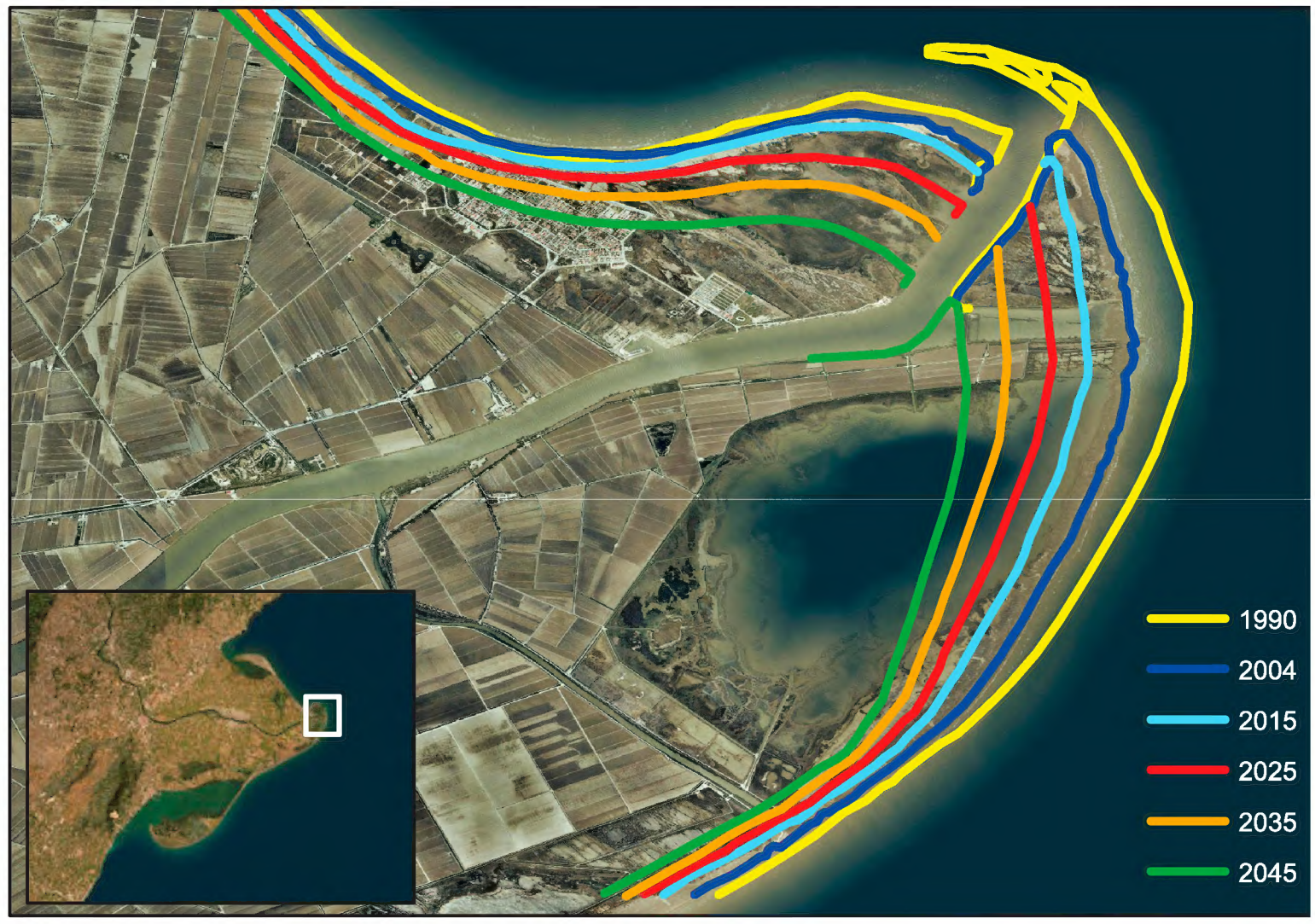

Figure 2. Observed and projected shoreline evolution for one of the most vulnerable stretches on the Ebro Delta coast, located at its eastern apex and corresponding to an old river mouth. The simulated evolution (Sánchez-Arcilla et al. 2008) shows a progressive rounding of the shoreline for decadal invariant wave conditions and SLR projections corresponding to the SSP2 – RCP4.5 scenario of AR6 from IPCC (IPCC 2021).

Figure 3. Range of alongshore sediment transport rates (yearly averaged), for a set of characteristic points along the deltaic coast (modified from CEPYC/CEDEX work on Google image from the final Plan Delta report). For each point, the maximum, minimum and central trend estimates are shown, together with over-wash transport over the barrier beach in the southern delta (removing sand from the outer coast).

adjusted CERC equation (Sánchez-Arcilla et al. 2008; Grases et al. 2020). These estimations have been supplemented by sand budget calculations, using aerial photographs and locally verified closure depths (e.g. Gracia et al. 1998). The transport rates represent the average and extremes of the obtained variation intervals for the last 50 years, where the central values for the average longshore transport at yearly scales are associated with the sand budget summarised in Table 1. This Table illustrates the variability of the sediment budget for the sand fraction, depending on the deficit definition, the sector of delta considered and the time-frame for the performed analyses. An average estimate of the sand deficit, defined as the longshore sand transport that yearly goes from the outer deltaic coast into the two bays (northern and southern) can range from approximately 50,000 to 500,000 m^3/yr, with 20,000 to 130,000 m3/yr corresponding to the NOrthern hemi-delta and 30,000 to 370,000 m^3/yr to the southern hemi-delta. This loss for the outer coast is mainly transported into the bays, with additional deposition by storm-induced over-wash into the more favourable sectors of the deltaic plain. Although the net budget at yearly time-scales may be balanced, the coarse sediment entering the bays becomes mixed with much finer fractions and it would be, thus, difficult to recycle for nourishments on the outer coast. The same happens with over-wash deposits on the deltaic plain, which leads to a sand deficit for the outer coast bounded by an overall amount of about 500,000 m^3/yr. This deficit, compounded by practical limitations to use sediment mixes from the bays or deltaic plain, represents the sand volume lost from the outer, wave dominated coast, stemming from: a) longshore transport around the two spits; b) across-shore transport towards the plain by over-wash or towards the offshore by undertow, rip circulation and gravity ; c) cross-shore transport at longer scales due to relative sea-level-rise, often estimated with Bruun's rule; and d) evolution of the active cross-shore zone, which may change due to RSLR and coastal curvature, leading to further losses of sand no longer located in the "active" profile. These fluxes have been aggregated into a net onshore transport (by wave asymmetry) and a net offshore transport (by sea-level-rise and beach profile changes) at a variety of time-scales and are hard to estimate robustly due to the need of additional hypotheses for the calculations (Sánchez-Arcilla et al. 1996).

Table 1. Sediment balance along the Ebro Delta coast (m^3/year), indicating authorship and year when the analysis was performed (CEPYC 2021). Negative values mean deficit.

Authorship	Northern hemi-delta	Southern hemi-delta	Main sources	Main sinks		Total balance
				N Bay (Fangar)	S Bay (Alfacs)	
GENCAT (1991)	-123,000	-287,000				**-410,000**
Guillen and Palanques (1992)	-415,000	-1,191,900				**-1,566,050**
Jiménez and Sánchez-Arcilla (1993)	0/-30,000	0	0/30,000		16,000	**-16,000/-46,000**
LIM-UB (2000)	0	0		63,000	16,000	**-79,000**
GENCAT (2008)	-8,000	-102,000				**-110,000**
LIM/UPC (2011)	-73,000	-358,000				**-432,500**
CEPYC (2021)			30,000	30,000	150,000	**-150,000**

The aggregated estimation is also evolving with time, reflecting the cumulative influence of reduced river sediment input and deltaic shape evolution, as indicated in Table 2 (CEPYC 2021). It becomes apparent that there is an increasing sedimentary deficit, explained by the cumulative starvation associated with decreasing riverine input and increasing RSLR.

The estimated sand deficits exceed the volumes deposited in sink areas (the two bays and selected back beach stretches) as can be observed in Table 2, indicating net losses, as should be expected with any active coast with significant sedimentary fluxes and where most cross-shore transports have not been considered. This is because of the uncertainty in aggregated cross-shore transport and because the different cross-shore mechanisms change in relative weight along the outer coast (e.g. over-wash only active in low berm-level profiles, which also evolves with time). Such a deficit mainly affects the southern hemi-delta, with about two-thirds of the total value, while the northern hemi-delta, with a shorter coastline and receiving most of the river-borne sand, is experiencing only one third of that deficit. The over-wash cross-shore transport, occurring mainly over narrow beach stretches like, for instance, in the southern hemi-delta barrier beach, accounts for a small percentage of the deficit. This can be illustrated by the over-wash volume deposited in the lee side of the long and narrow spit in the southern hemi-delta, whose net value has been estimated as 23,000 m^3/yr (Fig. 3).

The performed analysis leads to two main sink areas in the northern and southern deltaic bays, amounting, respectively, to approximately 90,000 m^3/yr and 276,000 m^3/yr during the last decades of the last century, before river regulation completely altered the entire deltaic coast. Current sink volumes are likely significantly smaller, as illustrated by the net sediment transport rate passing the southern hemi-delta spit apex, which is approximately 150,000 m^3/year. This means that the present sink volume inside the bay, considering the effect of river regulation and dam system, should be around half of that for pre-dam conditions (from 1900 till 1970 approximately). The same applies to the northern delta spit and associated coastal bay, where the spit apex is growing now at significantly smaller rates (Sánchez-Arcilla et al. 2022).

Deltaic coast evolution has been projected at climatic (decadal) scales considering RSLR acceleration and assuming invariant wave/surge conditions during the second part of this century (Sánchez-Arcilla et al. 2008; CEPYC 2021). Coastal projections have been estimated for the 2045 and 2100 horizons and for the SSP2-4.5 and SSP5-8.5 scenarios, to be comparable with the rest of the Spanish coast adaptation plans. According to the common methodology for the Spanish coast, the 99.9% surge has been included in the projected coastal evolution.

Table 2. Summary of sedimentary balance estimates (m^3/year) over different time intervals (CEPYC 2021).

Interval	Total deficit	Main source (river)	Main sinks (excess)
1957–2018	**-150,100**	30,000	180,100 (0)
1984–2018	**-150,000**	30,000	180,000 (0)
1994–2018	**-397,480**	30,000	366,000 (61,480)
2004–2018	**-379,796**	30,000	366,000 (43,796)
2015–2018	**-489,060**	30,000	366,000 (153,000)

Since several state-of-the art projections indicate a potential decrease of significant wave height and the same for storm surge, while others suggest an increase in the energy and frequency of storm peaks (Sierra et al. 2020; DeLeo et al. 2021; Lira-Loarca et al. 2021), the performed analysis has assumed invariant wave and surge conditions, applying present probability distributions to future decades until 2100. However, a potential shift in incoming wave direction (Sierra et al. 2023), associated with a higher percentage of southern wave storms, has been considered for the designed natural sand conveyor belt, which enhances sand recycling and reduces the cost, impact and carbon footprint of coastal maintenance. The planned sand recycling belt in the northern deltaic coast (described in section "Alternatives for coastal resilience: morphological roughness and sediment recycling") and the maintenance programme for the southern barrier beach consider both the alternating wave trains that dominate met-ocean conditions in the area, where southern waves underpin beach recovery after the "traditional" north-eastern storms. The observed concentration of wave energy into more frequent impulsive storms (Makris et al. 2023) suggests enhanced erosion and flooding in the coming years, compounded by RSLR. This would mean higher risks for coastal areas, especially those fronted by a narrow beach, particularly the Trabucador bar, whose breaching, if not compensated by human action, may lead to an accelerated evolution of the deltaic coast, with spits evolving towards islands disconnected from the main deltaic body (e.g. Gal et al. 2021).

The estimated averaged net sediment transport along the coast is summarised in Table 3, which describes a sediment-starved deltaic coast that, despite the lack of coastal structural barriers, such as groynes, is no longer pristine due to the decreasing riverine solid transport. This decrease, combined with accelerating RSLR, around 4 mm/year under current conditions, would require an extra 200,000 m^3/yr of sand to compensate for RSLR induced erosion. The combined deficit due to wave action and RSRL would then be of order 700,000 m^3/yr. The wave component is expected to decrease in the coming decades, due to the reshaping of the deltaic coast, while the RSLR part is expected to increase due to

Table 3. Longshore sediment transport (Sl) for the Ebro Delta coast in m^3/year (CEPYC 2021).

Coastal stretch	Max. Sl	Min. Sl	Average net Sl
1 N spit (Fangar) tip	333,000	25,000	120,000
2 N spit (Fangar)	550,000	45,000	142,000
3 N most beach (Marquesa)	125,000	17,000	57,000
4 N central beach (Riumar)	240,000	-206,000	52,000
5 River mouth area	255,000	30,000	117,000
6 E cape (Cabo Tortosa)	104,000	-90,952	8,500
7 S of river beach (Isla Buda)	724,000	105,000	237,600
8 S central beach (Eucaliptus)	870,000	55,000	198,000
9 N barrier beach (Trabucador)	480,000	11,000	139,600
10 Centre barrier beach	470,000	5,989	180,000
11 Over-wash barrier beach	30,000	16,000	23,000
12 S spit centre (La Banya)	692,000	48,000	210,000
13 S spit south (La Banya)	895,000	82,874	295,000
14 S spit tip (La Banya)	595,000	0	154,000

climatic change acceleration. Due to that deficit and the present sand scarcity, nature-based solutions offer a good potential to enhance coastal resilience with limited impact and carbon footprint. Such an approach is better suited to the projected future scarcity of freshwater, offering one of the most efficient types of intervention to increase coastal resilience under future climatic conditions.

Alternatives for river-delta connectivity: sediment mobilisation and transport

Feasible technical options for reservoir bypass

There is a wide range of techniques for sediment management in reservoirs which can be classified into three broad groups (Kondolf and Farahani 2018): a) protective measures which reduce sediment entry into the reservoir; b) evacuation measures which transport sediment through or around the reservoir; and c) recovery measures which remove sediment from the reservoir. These options have been analysed for the Mequinenza-Ribarroja-Flix Reservoir system in the lower Ebro course (Garrote 2018), concluding that the most actionable solution to mobilise reservoir sediments is the removal of deposited material by hydrodynamic (flushing or sluicing) or mechanical (excavation or dredging) means. Flushing was analysed (Garrote 2018) with the Tsinghua model, an empirical procedure that allows the estimation of washing results depending on the geometric characteristics of the reservoir and based on a set of successful flushing experiences in China (Atkinson 1996). Although the Tsinghua method provides acceptable sediment mobilisation in Mequinenza, the conditions of this Reservoir are not favourable to flushing, because the Basin is quite long and the capacity of the bottom outlets (160 m^3/s) is rather limited. The water levels that can be reached before controlled discharges do not provide enough flushing capacity, since a large volume of water (from 100 to 200 hm^3) still remains impounded in the Reservoir during the flushing operation. Furthermore, the sediment mobilised at the tail of the Reservoir would have to travel more than 100 km across the Reservoir with a mild slope before reaching the bottom outlets. A large fraction of the mobilised sediment would be, thus, deposited in the Reservoir before any possible evacuation through bottom outlets. Consequently, it can be concluded that flushing presents technical difficulties in the Mequinenza Reservoir.

The empirical formulae of the Tsinghua model provide better results for the case of downstream Reservoirs Ribarroja and Flix. With a washing flow rate of 200 m^3/s in Ribarroja, a sediment concentration of approximately 60 kg/m^3 can be expected, which would allow 1 Mt of sediment to be evacuated in one day. With a different methodology (Flumen Institute 2022), it was determined how the sediment evacuated depended on the reservoirs' water level, reaching approximately 600,000 t of sediment per day in the present situation for a water level of 60 m and a discharge of 2000 m^3/s. As a result of this analysis, it can be concluded that, in principle, sediment flushing is technically possible in both reservoirs, although there is a need for deeper analysis on the environmental and socio-economic impacts and benefits of such operations. An efficient flushing requires an almost complete emptying of the reservoir, followed by a period of sediment evacuation and a period in which the storage of the

reservoir is recovered. These three processes can have significant environmental and socio-economic effects in the reservoir and further downstream. The water released during the emptying of the reservoir comes from the lower layers, with a lower water quality than the surface layers. It is also common that the material settled at the bottom of the reservoir is active from a biochemical point of view, so the water in the lower layers is exposed to the re-suspension of this material. Furthermore, emptying the reservoir leads to a reduction in stored volume and flooded area, with possible negative impacts on biological communities. In addition, flushing evacuates water with high sediment concentrations that could induce significant environmental impacts down the river.

From a socioeconomic standpoint the main effects would come from the hydroelectric production and many other interests related to the management of the lower Ebro reservoirs, all associated with the management of available freshwater volumes. Present uses of downstream water would be potentially altered by the high concentration of suspended solids and by the possible mobilisation of toxic substances accumulated in the reservoir sludge. The water supply intakes along the lower Ebro, recreational uses or the cooling of the Ascó nuclear power plant are the most obvious problems, while the potential benefits from an enhanced sediment supply to the lower Ebro River and the Delta include reduced coastal erosion and subsidence, recovery of the river ecosystem and improved environmental conditions for native versus invasive species (Ibáñez et al. 2020a, b). In summary, there is a broad set of interconnected environmental, economic and social impacts that must be considered when planning flushing operations.

Mechanical sediment removal procedures are always technically feasible, their main limitation being cost and carbon footprint. Data collected from a number of worldwide experiences (Morris and Fan 1998; Anchor 2020), corresponding to favourable situations for this technique, show that its implementation is associated with relatively high costs. Hydraulic dredging seems to be the only feasible alternative to significantly remove bulk sediment from the reservoirs. Recent work by the US National Reservoir Sedimentation and Sustainability Team (Anchor 2020) has analysed economic data from several decades of dredging lakes and reservoirs in the U.S., proposing several tables for order-of-magnitude cost estimates of such operations. The cost of hydraulic dredging by 14- to 18-inch cutting suction dredge was estimated between 10 \$/m^3 and 20 \$/m^3 for mid-size projects from 75,000 to 750,000 m^3/yr. The lower bound of this bracket would allow the bypassing of 0.15 Mt/yr at a cost of roughly 700,000 €/yr. The upper bound would reach 1.5 Mt/yr at a cost of roughly 14 M€/yr, but these figures depend largely on local conditions. Several pilot experiments are envisioned to test the technical and economic efficiency of this procedure for the lower Ebro River, with the aim of designing a long-term system of sediment bypass in the Ribarroja and Flix Reservoirs (Ibáñez et al. 2020b). These pilot tests will assess the amount and nature of the sediment that can be by-passed, particularly the sand and silt fractions that can be mobilised.

Activities for sediment mobilisation

The Ebro Basin Management Plan for the period 2021–2027 includes a wide range of initiatives to characterise sediment transport in the lower Ebro and to explore alternatives for sediment downstream mobilisation. Present sediment

transport in the lower course of the river has been analysed to define the most appropriate corrective measures that increase sediment delivery to the Delta. The first step was to conduct new bathymetric surveys for the Mequinenza and Ribarroja Reservoirs and the lower course of the Ebro River (from reservoirs to river mouth), as well as field campaigns for sediment characterisation. Sediment samples confirmed the high armouring level of the bed in the lower course between Flix and Tortosa (Fig. 4), where more than 80% of the sampled material was coarse-grained gravel and sand only appeared in significant amounts downstream of Tortosa. The information obtained in these studies is essential to develop a correct numerical model of sediment transport in the

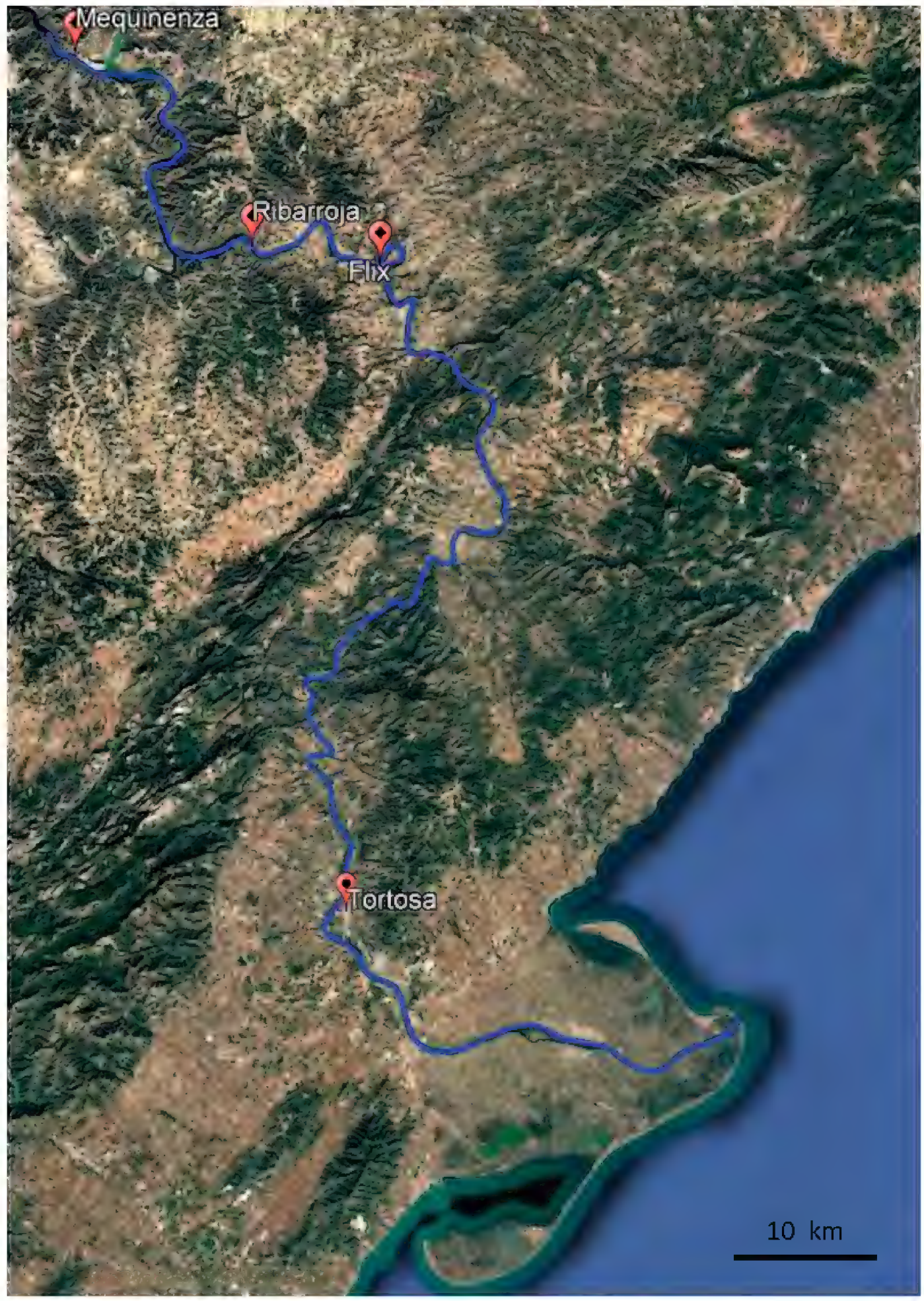

Figure 4. Location of the Ribarroja and Mequinenza Reservoir system, including the Flix weir, Tortosa City and the Ebro DELTA (source: Google Earth).

Ebro River, required to evaluate the effectiveness of proposed alternatives for sediment mobilisation and transport.

The River Basin Management Plan also explored the funding necessary to carry out these operations, in coordination with all affected stakeholders, considering a series of pilot tests to mobilise retained sediment, with the necessary safeguards for the environment, security and economy of the population. Pilot tests have been carried out at the tail end of the Ribarroja Reservoir, in the regatta area of the town of Mequinenza. By lowering the water level of the Ribarroja Reservoir during flood flows in the Segre River, the hydraulic gradient in the tail of the Reservoir is enhanced, facilitating the erosion of deposited material, where the sediment extraction can be supplemented by mechanical and hydraulic dredging. Another test will analyse the viability of extracting sediments from the Matarraña River deposits, near where it joins the Ebro River in the Ribarroja Reservoir (López-Gómez et al. 2024). This on-going test analyses the technical and economic feasibility of a sediment transport system that combines: a) hydraulic suction of bottom sediments and transport by floating pipes to the downstream side of the Ribarroja dam; b) sediment flushing in Ribarroja by lowering the reservoir water level during high flows; and c) introduction of sediment from the mouth of the Siurana tributary deposits into the Ebro River. During recent storms (e.g., Gloria storm in January 2020), a significant volume of sedimentary material was accumulated near the Siurana-Ebro confluence, which is limiting the conveyance capacity of bridges across the Siurana River. These deposits are planned to be transported to the Ebro River bed, monitoring downstream sediment transport by isotopic tracers and electromagnetic transmitters to generate data for the calibration of numerical transport models. These data include surveying reservoir and river morphology and mineralogical characteristics of accumulated sediments, providing the basis to assess the feasibility of such sediment mobilisations from technical, environmental and socio-economic standpoints.

Technical feasibility has been assessed from model runs that, although without a detailed calibration, show that, to facilitate sediment drag, it is more efficient to deposit the material forming a transverse dyke than in a longitudinal arrangement. These analyses and data provide essential information to steer sediment mobilisation and downstream transport alternatives that underpin the mid- to long-term sustainability of the Ebro Delta. Restoring river to coast sedimentary fluxes is a challenging task fraught with technical, economic and environmental uncertainties that condition efficiency and associated impacts, which explains the slow adoption of river solid transport restoration in spite of the preparatory work done.

Downstream sediment transport to the Delta

Assessing downstream transport and comparing mobilisation measures requires a sediment transport rating curve, which has been prepared for the lower Ebro River with the aid of simulations. The numerical Ebro model (López Gómez et al. 2024) was built using the most recent bathymetric survey that goes from the Flix Reservoir to the Ebro Delta and is based on the Iber code (Cea et al. 2007; Bladé et al. 2014), which is a two-dimensional (2D) freely available code solving 2D hydrodynamic equations coupled to sediment transport equations.

The hydrodynamic part was calibrated using data from controlled flood observations, while the sediment transport was calibrated using previously compiled data (Ibàñez et al. 1996) characterising the annual transport of suspended sediments for several flow ranges in the Ebro River. Data covered the period before dam construction, derived from Gorria's experiments, conducted in 1877. From this analysis, two representative regimes have been identified: a) normal flow, between 300 m^3/s and 1,500 m^3/s, with an estimated mean flow of 710 m^3/s, a duration of 256 days per year and an average sediment concentration of 0.9 g/l; b) annual flood, for discharges larger than 1,500 m^3/s, with a mean flow of 1,764 m^3/s, a mean duration of 11 days per year and an estimated sediment concentration of 7.2 g/l. Aggregated sediment transport was estimated to be 14.1 Mt/year for normal flow and 12.1 Mt/year for annual flood conditions. An additional contribution of 1.7 Mt/yr from exceptional floods was added to the aggregated annual transport, supplemented by 0.2 Mt/yr corresponding to flows of less than 300 m^3/s. These values result in a total annual discharged volume of 17.38 km^3/yr and an aggregated sediment transport of 28.1 Mt/yr. Numerical simulations were performed for the two identified flow regimes, estimating sediment transport parameters to fit the observed data until a good agreement was achieved. The model was then used to simulate other flows to build a complete sediment rating curve for the lower Ebro River.

Current potential sediment delivery (*natural and altered conditions*)

The low transport rate, currently observed in the lower Ebro River, is due to the lack of available sediments, with a potential sediment transport derived from numerical simulations, observed flow data and the sediment transport rating curve. Present flow data are obtained from the Tortosa gauge station, where data are available from 1913, but with several small gaps and a larger one from 1936 to 1951. The period with continuous data spans from the hydrological year 1953–54 to 2019–20, the period for which potential sediment transport has been estimated by applying the sediment transport rating curve to daily flows measured in the Tortosa station. The average potential sediment transport is 11.11 Mt/y, two orders of magnitude larger than the currently observed sediment flow.

This figure can be compared to the potential sediment transport under the natural hydrologic regime, without any flow alteration produced by regulation and water abstractions. Flow data under natural conditions are obtained from the SIMPA model, Spanish acronym for Integrated System for Precipitation-Runoff Modelling. SIMPA is a conceptual distributed hydrological model that simulates the average monthly flows in the natural regime at any point of the hydrographic network of Spain. The available simulated period is between the hydrological year 1940–41 and the year 2019–20. Monthly time series of the flow corresponding to the entire Ebro Basin were obtained. The divergence between natural and observed flows began in the 1960s decade, when reservoir construction in the Ebro Basin allowed the development of irrigation and water abstraction. Although some irrigation is still being developed in the Basin, the large irrigation districts were completed in the 1980s. The average flow measured in Tortosa in the last 40 years with data is 9.09 km^3/y, while the estimate under natural conditions from the SIMPA model is 15.13 km^3/y. The difference of 6.04 km^3/y can be mainly attributed to irrigation abstractions. The

Ebro River Basin Management Plan for the cycle 2021–2027 considers 924,400 ha of irrigated land, with an annual demand of 8.1 km^3/y. The difference between natural and measured flow would correspond to a net loss of water to evapotranspiration of 75% of the bulk abstraction, which is a reasonable figure according to the state of the art (Döll and Siebert 2002; Wisser et al. 2008).

Although water abstractions are a key contributor to flow reduction, their impact on potential sediment transport is disproportionately larger due to the non-linear relationship between flow and sediment transport capacity. While other factors – such as reservoir retention and evaporation – also affect flow, abstractions significantly reduce peak discharges, which are most effective in transporting sediment. Potential sediment transport was estimated by applying the sediment transport rating curve to monthly flows, where the average value in the last 40 years is 22.39 Mt/y under natural conditions and 6.93 Mt/y under actual altered conditions, a 70% reduction versus 42% for annual flow. This figure sets an upper limit of the sediment that should be bypassed from the reservoirs unless specific measures are adopted to enhance the sediment transport capacity of the river through periodic controlled floods.

The bracket between 0.15 Mt/yr and 1.5 Mt/yr previously obtained when analysing feasible technical options for reservoir bypass, would produce a sediment discharge between 75,000 m^3/yr and 750,000 m^3/yr. The cost would be between 0.7 M€/yr to 14 M€/yr, with a sand fraction in the dredged material depending on local conditions. The Ebro River Basin Authority has recently carried out a sedimentologic analysis of Mequinenza and Ribarroja Reservoirs (CHE 2023). They found out that the Shepard diagram shows a dominant clay-silt texture for sediments deposited in the Reservoir (predominantly at Mequinenza where most of the fine particles are retained). Most of the samples contain a sand fraction between 0% and 40%, with a mean value of 18.5% in Mequinenza and 7% in Ribarroja, where dredging operations will most likely be carried out. Assuming 10% of sand fraction, the sediment discharge under actual altered conditions amounts to an aggregated sand discharge of about 7,500 to 75,000 m^3/yr, which is between 1% and 10% of the 700,000 m^3/yr coastal sand deficit estimated above.

It should be noted that the application of the rating curve produces different results for daily and monthly flows due to its non-linearity. The rating curve shows that downstream sand transport requires a minimum flow of approximately 575 m^3/s and this threshold was exceeded in 146 months in the last 40 years under natural conditions (30% of the time) and only in 59 months under altered conditions (12% of the time).

Future potential sediment transport (under climate projections)

Estimates of potential sediment transport for future scenarios can be obtained using climate projections taken for this analysis from the AgWaMed project, in which climate projections were analysed for all Mediterranean Basins (Garrote et al. 2023). Although three IPCC AR6 scenarios have been considered (SSP1-2.6, SSP3-7.0 and SSP5-8.5), only the latter will be discussed here, since it is the most pessimistic one and has also been applied for coastal projections. Data have been obtained from the ISIMIP (Inter-Sectoral Impact Model Intercomparison Project) repository, a collaborative research effort to assess the impacts of climate change on various social and environmental sectors. The hydrological

regime of the Ebro Basin has been derived from the global hydrological models H08 and CWatM, available in the ISIMIP repository.

Two sets of climate scenarios have been used: historical scenarios (for past times) and future scenarios (for future times). Selected historical scenarios from ISIMIP are of two types: *obsclim* and historical. The denomination *obsclim* corresponds to impact models forced with observed climate in the actual time sequence, based on re-analysis data and selected here to validate the runoff obtained with the two global climate models against the results of the SIMPA model in the historical period. Historical data correspond to impact models forced with results from climate models, selected as a control reference to estimate changes of potential sediment transport under future conditions. The SSP5-8.5 simulations for future times start in 2015 and end in 2100, with hydrological models forced by two types of climate drivers: a) based on observations and b) based on climate models (H08 and CWatM).

These simulations are summarised in Table 4, featuring the projected potential sediment transport rates under natural conditions and showing the significant variability across models and scenarios, as well as the high uncertainty of potential sediment transport estimation. These results underscore the vulnerability of sediment delivery to the Ebro Delta under climate change and the importance of integrated river and sediment management.

Obtained projections show a significant difference between the mean potential sediment transport from the SIMPA model and those estimated with the two global hydrological models, despite the bias correction. For the *obsclim* scenario, the SIMPA model estimate is 22.68 Mt/y, while H08 provides a mean sediment transport for the Ebro River of 15.61 Mt/yr (31% less than SIMPA) and the CWatM estimate is 31.01 Mt/y (36% more than SIMPA). These estimates are, therefore, highly uncertain. The values for the average over the five climate drivers of the historical scenario are 23.24 Mt/y for the H08 model and 38.11 Mt/y for the CWatM

Table 4. Average potential sediment transport (Mton/yr) under natural conditions in the Ebro River according to the selected model, scenario and time period.

Scenario	Obsclim	Obsclim	Historical	SSP1-2.6	SSP3-7.0	SSP5-8.5
Period	80–19	75–14	75–14	60–99	60–99	60–99
SIMPA	22.68	21.60				
h08_gswp3	15.61	19.06				
h08_gfdl			20.50			
h08_mri			23.33			
h08_ipsl			23.92			
h08_mpi			21.54			
h08_ukesm1			26.93			
mean h08	15.61	19.06	23.24			
cwatm_gswp3	31.01	34.38				
cwatm_gfdl			36.95	35.93	26.43	23.38
cwatm_mri			39.95	43.20	43.91	33.19
cwatm_ipsl			36.95	37.62	26.76	18.49
cwatm_mpi			40.00	34.13	19.21	21.15
cwatm_ukesm1			36.72	35.66	25.46	22.54
mean cwatm	31.01	34.38	38.11	37.31	28.35	23.75

model. The corresponding values of the *obsclim* scenario for the historical period, 1974–1975 to 2013–2014, are 19.06 Mt/y for the H08 model and 34.48 Mt/y for the CWatM model. The projections for future scenarios show more variability than in the case of annual flows and the potential for sediment transport under natural conditions is expected to decrease dramatically in some scenarios.

The projected reductions in mean annual flow will dramatically reduce the sediment transport capacity of the Ebro River under natural conditions, due to the non-linearity of the sediment transport rating curve. Climate models H08 and CWatM produce different absolute figures, but the relative projected evolution is similar in both models. The impact of flow reductions on the potential sediment transport capacity of the Ebro River under altered conditions will depend on how the Ebro River is managed in the future, which will be conditioned by future climate scenarios and the projected socioeconomic evolution for the whole Basin. Under the current management strategy, roughly 6 km^3/y are abstracted from the 15 km^3/y of natural flow, leaving a 9 km^3/y discharge in Tortosa. This reduces the potential river sediment transport capacity from 22 Mt/y under natural conditions to 7 Mt/y, showing a deficit of about 15 Mt/y, which illustrates the amount of sediment required to maintain the geomorphic equilibrium of the Delta. The projected reductions suggest a future mean annual flow between 12 km^3/y and 13.5 km^3/y. The potential sediment transport capacity under the natural regime is expected to be reduced to an interval between 10 Mt/yr and 17 Mt/yr. If the river flow under altered conditions was similarly reduced, it would fall to a range between 3.5 km^3/yr and 5 km^3/yr with some river solid transport capacity still remaining. However, if the current abstractions of 6 km^3/yr are maintained in coming decades, the available flow would be reduced between 6 km^3/yr to 7.5 km^3/yr, which represents a larger reduction than that of the natural flow. Therefore, it is very likely that the potential for sediment transport under altered conditions may be severely reduced when compared to solid discharges under natural conditions, with significant effects on the deltaic evolution in case sedimentary river-delta fluxes are re-established.

Alternatives for coastal resilience: morphological roughness and sediment recycling

The scarcity of water and sand supplies from the Ebro require maximising the natural resilience of the deltaic coastal fringe, formed mainly by sand and directly exposed to erosion and flooding from incoming waves and surges. As a main result of this study, two alternatives have been designed and tested through pilots: a) increasing coastal roughness by means of embryo dunes that mimic old dunes in times of richer sedimentary input from the river; b) sand recycling by a natural belt that combines aeolian and wave induced transports.

Increased coastal roughness by embryo dunes plus a ridge and runnel morphology

This solution has been designed, tested and implemented for two pilot sites: a) longitudinal embryo dunes combined with shore-face pointwise nourishment for the Trabucador bar (southern hemi-delta); b) transverse embryo dunes combined with a ridge and runnel morphology created by embryo lagoons for the Marquesa

beach (northern hemi-delta). Both designs (Figs 5, 6) have considered present met-oceanographic conditions, sand deficit constraints and the acting relative sea-level rise. The performance of these solutions, which mimic natural deltaic forms from old aerial photographs, is being periodically assessed by drone images and in-situ met-oceanographic data, suited to the intermittent plan for reconstruction, that must be compatible with the important ecological values in the area (construction goes from September to February to avoid the breeding season).

Despite the lack of universally accepted standards for barrier beach sustainability, the proposed restoration aims to generate partial barriers instead of continuous ones, that result in a sluggish morphology (Masselink and Gehrels 2015) without preventing natural over-wash. This is achieved by constructing

Figure 5. Illustration of embryo staggered (longitudinal) dunes constructed along the Trabucador beach (southern Ebro hemi-delta), testing the partial barrier concept, which refers to barriers that allow cross-shore transport and that restore coastal roughness. Partial barriers in narrow barrier beaches enable over-wash fluxes without preventing the back-beach growth for natural resilience.

Figure 6. Illustration of wind normal embryo dunes to promote controlled aeolian transport for a sand recycling belt (left) and embryo lagoons to promote naturally a ridge and runnel topography (right).

an alternate embryonic dune system that can: a) be easily over-washed to feed the back beach and thus maintain the barrier resilience; b) reduce the breached volume facilitating natural or artificial recovery (Sánchez-Artús et al. 2024a, 2024b). The performance of alternating embryo dunes (AD) has been compared in terms of morphodynamic evolution and erosion/flooding with the same beach with no protection (NP), analysing the morphodynamic evolution. Moreover, to evaluate the efficiency of the AD approach against more traditional interventions, it has also been compared with both a continuous dune strategy (CD) and classical nourishment (CN) (Fig. 7). The beach evolution has been observed and simulated with a validated hydro-morphodynamic model for two types of characteristic storms in the area, representing energetic (Filomena in January 2021 and Isaak in February 2023) and extreme (Gloria in January 2020, largest storm ever recorded in the Catalan coast) events.

The numerical model, XBeach is well suited to analyse barrier beach performance (Sallenger 2000; Roelvink et al. 2009) and, thus, has been used as a diagnostic tool to steer the design of embryo dunes to maximise restoration resilience. Breached volumes under storm events are similarly reduced, except for the extreme storm, but only the AD intervention feeds the back beach enhancing its natural resilience for next storms. A careful calibration of the model fit parameters has ensured that the typical erosion overestimation

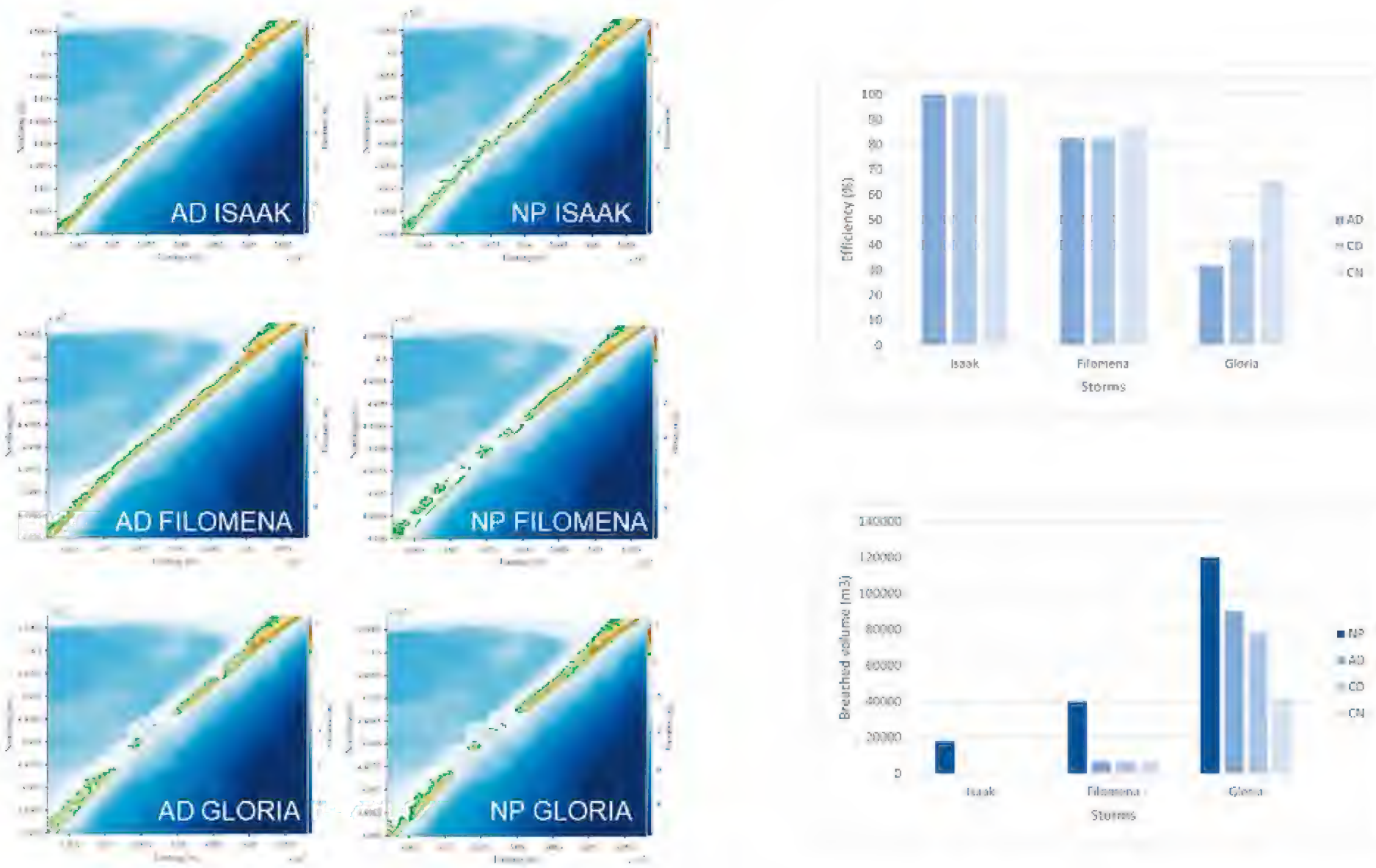

Figure 7. Simulated barrier beach (Trabucador bar in the southern Ebro Delta) breaching under three storm events and for the no protection (NP) as a reference case versus different restoration actions to increase coastal roughness and nourishment durability in the emerged beach. The two left hand side columns illustrate the barrier beach performance in plan-view for the NP and alternating embryo dunes (AD) situations, while the two right hand side images characterise the breached volume (upper) and the efficiency of the initial nourishment volume in terms of the volume remaining after the storm. The comparison should enable a ranking of NP, AD, continuous dune (CD) and classical nourishment (CN) interventions as a function of initial state and climate conditions.

was bounded, so that the performed comparison has been applied to the actual embryo dune design and construction. Numerically simulated beach responses have been compared to Sentinel-2 data (Sánchez-Artús et al. 2024b) and are now being used together with satellite and drone data to monitor the evolution of the coastal stretch and to assess the effectiveness of the enhanced coastal roughness to reduce erosion and flooding, while increasing the durability of the restored embryo dune field. Fig. 7 shows the breached volume, defined as barrier beach areas with a water depth larger than the spring tidal range (0.3 m), ranging between 17,000 to 120,000 m^3 in the absence of protective interventions (NP case). The embryo dune protection reduced this breached volume to values between 5,000 m^3 and 30,000 m^3 for energetic and severe storms, respectively, suggesting the need to enhance the active profile dissipation capacity by increasing the beach width (e.g. via shore-face nourishment) and the beach roughness (e.g. via irregularly placed embryo dunes). The level of protection improves with a proactive deployment, where the beach width and roughness are enhanced before the storm impact. This rapid defence measure (deployment time of order 1 week) further reduces breaching, particularly for the most extreme events that combine very high wave energy with a surge above 0.5 m, demonstrating the potential of coastal roughness generated by embryo dunes to reduce breaching volumes by a factor 5 to 10 (Sánchez-Artús et al. 2024a). For low to medium energy storms, the efficiency of the embryo dunes, defined as the reduction of breaching compared to the no protection case, was close to 100% and, even during high-energy events, the breached volumes were reduced by about 30%, as can be seen in Fig. 7. The enhanced coastal roughness achieved by embryo dunes, smaller at the foreshore and larger at the backbeach/berm, but always maintaining their partial barrier characteristics, has proved to be a naturally resilient system when compared to more conventional dune fields that aim to generate full barrier effects.

The transverse dunes with embryo coastal lagoons (Figs 6, 8) have been designed and tested at the northern deltaic fringe, showing how the small dunes, orientated transversely to the dominant wind direction, may enhance the durability of the sand supplied on the emerged beach. These embryo dunes increase the natural resilience against erosion and flooding, without generating sand flooding in hinterland areas, which would compromise socioeconomic activities and reduce the volume of available sediment for the active coastal profile. The dune field has been partially fixed in downwind areas, where aeolic transport would push the supplied sand into the river mouth and, thus, out of the nearshore zone, by vegetation and sediment traps, well suited to the available accommodation space and sand volumes. These dunes and the lagoons are developing a rough coast with a ridge and runnel topography, characterising a sluggish morphodynamic state that, therefore, enhances beach resilience and the durability of artificially supplied sediment. The evolution of this type of intervention is now being monitored by satellite and drone data, but the observations, although showing higher durability than conventional nourishment, are still too short to derive robust conclusions on performance under cumulative storm action. The initial assessment indicates a higher capacity to dissipate incoming wave and surge energy (for a given beach width) and, therefore, smaller erosion and flooding in the backbeach.

Figure 8. Sand recycling by means of a natural conveyor belt, combining aeolic and wave induced transports, designed to reduce the net sediment deficit at the end of this coastal stretch. The required artificial nourishment per year will, thus, be greatly reduced with respect to the volume needed otherwise (source: own work).

Sediment recycling by a natural conveyor belt that combines aeolic and wave transports

This solution has been designed, tested and implemented for one pilot site in the northern hemi-delta (Fig. 8). Transverse dunes migrate towards the SE, moving closer to the river mouth area and are driven by the prevailing NW winds (e.g. Sánchez-Arcilla et al. 2023). Net alongshore transport in the nearshore zone is towards the NW, driven by both prevailing incoming wave systems (from ENE and from SW), which, regardless of their offshore direction, generate NW directed transport due to refraction and diffraction. Although aggregated estimations of the two opposing transports are being progressively refined, the two opposing fluxes (Fig. 8) show how they can provide a natural conveyor belt to recycle sediment and, thus, enhance the durability of limited-volume artificial nourishment (associated with the transverse embryo dunes mentioned above). To obtain an order of magnitude of the intensity of such a natural sediment recycling, aeolian transport has been estimated to be within the interval 25,000 to 200,000 m^3/year (Barrio-Parra and Rodríguez-Santalla 2014), while alongshore sediment transport in that area (Fig. 3) is in the interval 50,000 m^3/year to 60,000 m^3/year. This shows that the natural conveyor belt is not in dynamic equilibrium and that net aeolian transport may exceed wave alongshore transport, requiring a net redistribution of sand, at one of its ends, between 25,000 and 150,000 m^3/year. Such an amount supposes a much smaller volume than that required by conventional shoreface nourishments, since part of the sand deficit is naturally compensated by aeolian transport. This benefit requires, of course, regular wind patterns which are strong enough to generate an aeolian transport comparable to wave induced transport, such as happens in the considered beach. The result is particularly positive for sediment-starved areas like the Ebro Delta, where large volumes of sand for nourishment may not be available or may produce large (unacceptable) environmental impacts, in addition to the large costs and carbon footprint of traditional massive nourishments.

For the long-term sustainability of the Delta, the proposed beach nourishment volumes should be compared to projected riverine transports and sediment availability in reservoirs or submerged prodeltas, which represent relict deposits that, once consumed, will be difficult to replace.

Discussion: trade-offs and synergies in river-coastal restoration

Restoring river to coast connectivity and coastal dynamics offers a resilient alternative for coastal protection with a low carbon footprint and potentially lower costs and impacts, compared to conventional engineering interventions, specially under climate change scenarios. Such restoration, aligned with the new European Nature Restoration Law and the Green Deal, presents significant uncertainties such as the time needed for river-borne sediments to reach the river mouth or the duration of the new deposits on the active coastal zone. The Ebro River-coast continuum illustrates a case where an apparently pristine coast is subject to high relative sea level rise rates, decreasing riverine discharges and is progressively more affected by other climatic pressures such as freshwater scarcity and salinisation. The Ebro system can be a natural laboratory for more complex coastal environments such as larger deltas or even urban coasts, where the limited accommodation space available requires optimised NbS, such as the ones tested at the Ebro Delta. The applied simulation models have been updated to address the multiple interactions between social-ecological components in this deltaic system, becoming a useful approach for other coasts experiencing an increase in risk levels and where predictions can support proactive decisions for a shared benefit.

The resulting predictability is, however, limited, which affects the analysis of synergies and trade-offs in the design of restoration plans, although synergies (for instance, in managing scarce freshwater simultaneously demanded by irrigation and to maintain the delta) are an essential element to enhance the socioeconomic acceptance of restoration solutions. Likewise, trade-offs (for instance when considering the environmental impacts of artificial nourishment versus the reduction of erosion risks) must be identified and assessed before implementing any restoration to avoid unexpected effects that may reduce confidence in this type of solution for actual risk reduction under future climate change scenarios.

Synergies are a basic requirement for a successful restoration under climate-induced scarcity of resources such as freshwater (e.g. due to increasing temperatures that result in higher irrigation demands) or coastal accommodation space (e.g. due to narrower coastal fringes due to sea-level-rise). Synergic restorations will result in smaller needs of scarce natural resources, such as river water and sand volumes, which underlines the importance of positive interactions amongst different sectors and domains (e.g. upstream farming communities and downstream aquaculture and fishing communities). Trade-offs, properly defined and presented, will provide boundaries for the restoration implementation (e.g. controlled river discharges when there is not enough freshwater for competing uses), contributing to a co-definition of tipping points for adaptation pathways shared by researchers and stakeholders. Moreover, these trade-offs will add reliability to the integrated assessment of the proposed restorations, showing that there is no “one size fits all” solution under climate

change and that nature-based interventions, presenting as any other solution a flip side, can lead to smaller trade-offs under future climate scenarios.

This synergy-trade-off analysis should be applied to the proposed river and coastal restoration interventions, particularly for high vulnerability conditions and limited natural resources, as is the case of the Ebro Delta coastal fringe. The analysis is summarised in the following paragraphs, based on the previous sections results, for the three types of Nature-based-Solution (NbS) proposed: a) Sediment by-pass and controlled river floods; b) embryonic dunes and lagoons; and c) sand recycling and circular transport.

Sediment by-pass and controlled river discharges to restore river-coast connectivity for solid transport

Sediment transport is a highly non-linear function of water velocities, which means most of the solid transport occurs under flood conditions, particularly for the sand fraction. The implication is that river-borne sediments can only be transported efficiently downstream under controlled discharges, as described in previous sections. For catchment areas like the Ebro, where freshwater is a scarce resource, organising such controlled floods requires a careful balance between competing water uses and considering the possible economic and environmental effects and benefits. In spite of this, the monitored discharges so far show that by reducing reservoir water levels before the controlled flood may increase sediment concentrations by almost an order of magnitude.

The sediment transported downstream must re-fill the river course, where sand and finer fractions have been washed away since the large dams' construction, leaving an armoured bed in the sloping part of the river course, almost until Tortosa City (Fig. 4) near the beginning of the Delta. This implies that solid transport will first return the bed to a natural state, with enough sand to be reported downstream, before any significant amount of sediment may reach the coast. Nevertheless, the time needed for the solid transport to reach the coast will depend on flow rates, discharged volumes and the river hydrologic conditions, where the experience from other rivers (e.g. Warrick et al. 2015) indicate that the travel time to the coast does not necessarily need to be large, depending of course on the distance to be travelled. The finer sediment fractions should also be considered for controlled delivery to the deltaic plain, through the canal network or, more unlikely overbank flooding, all contributing to a much-needed vertical accretion to compensate subsidence. This introduces further uncertainties in the amount and timing for solid discharges to reach the coast, which should be considered for the sequenced implementation of these controlled floods and the associated coastal protection measures as described in the following paragraphs.

Embryonic dunes and lagoons

Enhancing coastal roughness by means of embryo dunes and lagoons, as described in previous sections, increases the natural capacity of beaches to dissipate incoming wave and surge energy, leading to sluggish morphodynamic states that enhance beach resilience. This is an important requirement for sand-starved beaches, like those in the Ebro Delta coast, which are receiving now a much smaller

supply from the river and where alongshore sediment transport rates have also decreased due to a more rounded deltaic shape that is more in dynamic equilibrium with incoming wave trains. Such a reduction of longshore transport does not apply to regions with gradients in wave conditions or shoreline orientations, where significant gradients still verify and lead to important accretive/erosive responses.

The reconstructed dunes and lagoons provide a natural buffer for incoming hydrodynamic energy, contributing to maximise the duration of new sand volumes, such as those expected to come from river-controlled discharges. Until they arrive, this local-scale geodiversity can be constructed with "relict" sand deposits in the emerged or submerged parts of the Delta, where any sequenced implementation plan will require monitoring the characteristics of such relict sand deposits (e.g. for submerged prodeltas associated with old river mouths) and the behaviour of the constructed dunes and lagoons. The design of small-scale forms is consistent with the scarcity of sand and accommodation space commonly found in squeezed Mediterranean beaches, aggravated by sea level rise and, in the case of the Ebro Delta, compounded by subsidence, which require a regular monitoring and maintenance to ensure a sustainable risk reduction under repeated storms also frequent in the Mediterranean stormy season.

Natural sand recycling

Establishing a closed sand recycling belt, where wind-induced transport compensates in average terms the wave-induced transport, is a natural approach to maintain beaches with limited external nourishment and longer duration and resilience. Such an approach can only be designed where wind and wave fluxes are regular enough and present comparable powers to consider an almost closed natural conveyor belt for the sand fraction, as presented before.

Wind transport can be regulated by dune construction with more or less stabilisation as a function of the vegetation cover. Wave induced transport can also be regulated as a function of coastal roughness, in terms of the dunes and lagoon also presented. Both processes need regular monitoring and assessment, to adjust wave and wind fluxes so that they may reach a dynamic equilibrium. Such an approach offers a higher durability for existing and new sediment deposits, with enough flexibility to adjust the design to changing climate conditions, which results in a low impact and carbon coastal protection. The flip side is a low cost, but continuous maintenance that should be based on the advance information provided by an early warning system (Fig. 9), where 5 to 7 days before the storm arrives, the most exposed beaches, such as the narrow barrier beach of the figure, can be simulated to analyse the predicted impacts. This information enables a proactive response (at a scale of days) to enhance beach protection with rapid deployment measures (Gracia et al. 2014), which can be illustrated by small dune construction or reinforcement, by sand-bag protection or by beach scraping. Such measures should be deployed within the time-frame of early warning systems, which is now 7 days and have been tested in several beaches, mainly in urban beaches requiring extra protection before the storm and where there was an administrative structure prepared to carry out such short notice interventions.

A similar analysis for climatic scales leads to a climatic alarm system (Fig. 10), providing advance information at decadal scales. This information

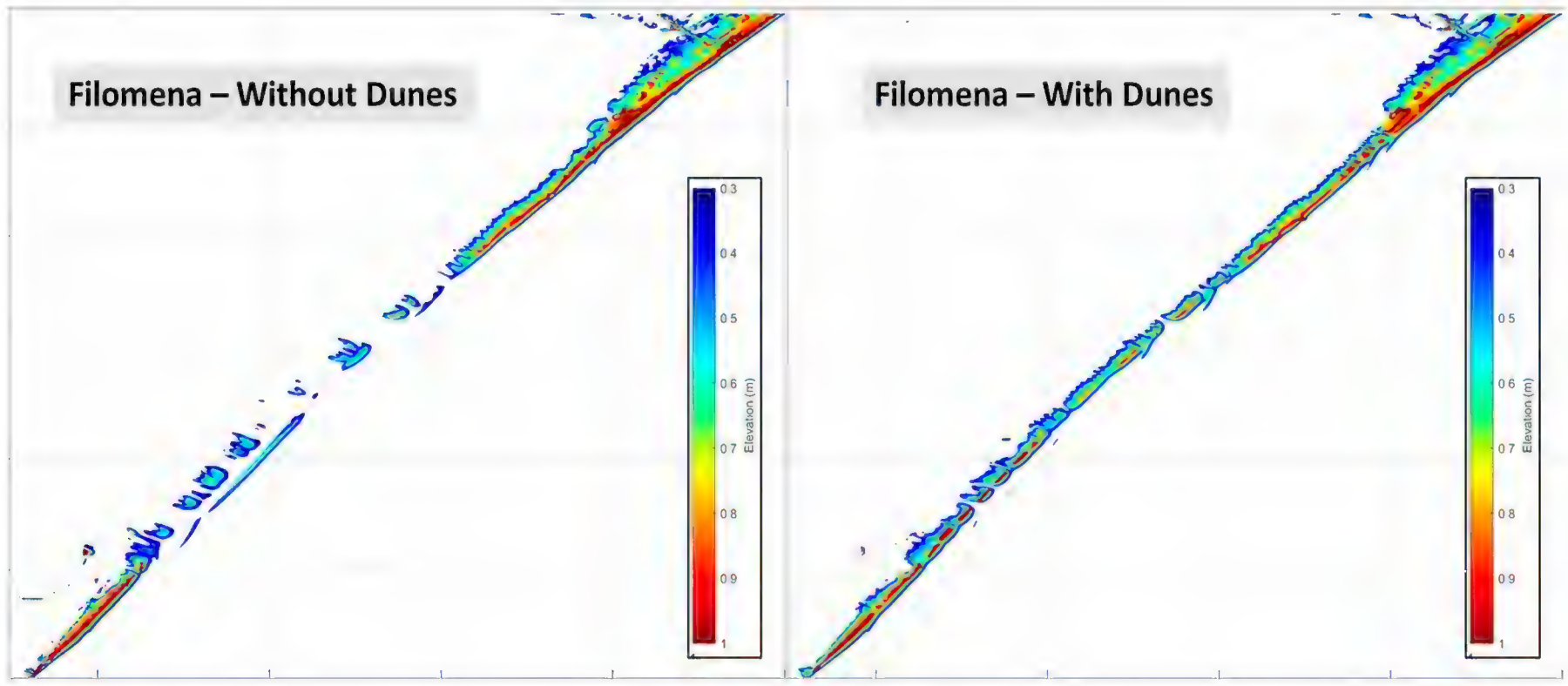

Figure 9. Prediction of breaching under an energetic storm for the Trabucador barrier beach in the Ebro Delta (after Sanchez-Artús et al. 2024b). The resulting breaching, predicted 5 days in advance, can be mitigated or prevented by means of additional coastal protection in the form of extra dunes, sediment filled bags or dissipative dune/trench systems. Filomena is one of the most energetic storms that affected this coast during January 2021.

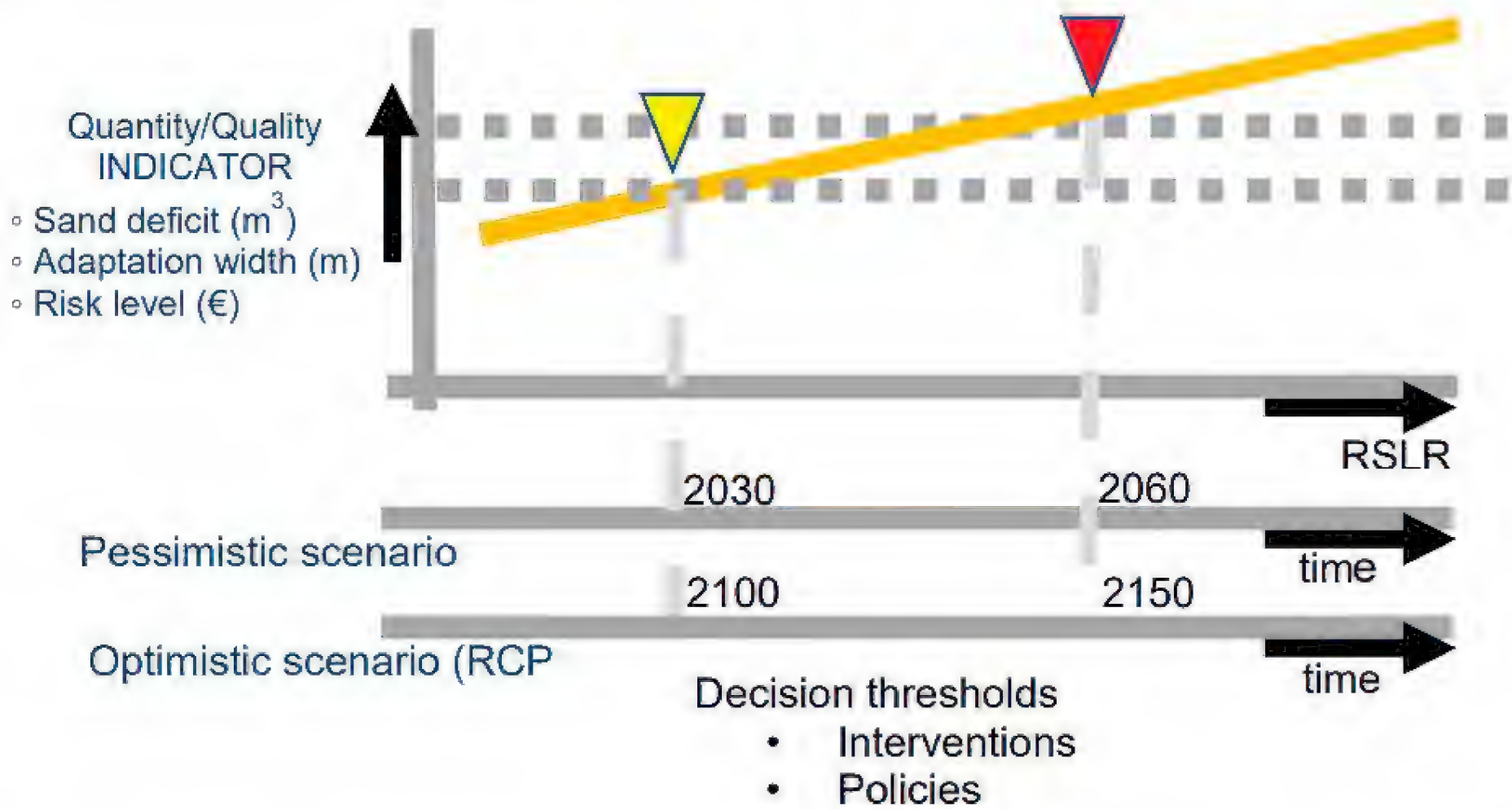

Figure 10. Climatic alarm system, projecting the evolution of key coastal protection variables, such as sand deficit, required adaptation width or risk level (vertical axis in arbitrary units). The projected evolution has been calculated in terms of relative sea level rise (RSLR), considering local rise due to global warming and subsidence. RSLR levels have been next translated into time horizons for two scenarios, co-selected with researchers and stakeholders from the REST-COAST EU Green Deal project.

is based on projected downscaled climate scenarios and refers to variables such as remaining beach width, available sand volume or estimated future risk levels. Whenever any of these variables or a combination reach a threshold associated with potentially damaging conditions (yellow arrow in Fig. 10), actions should be taken to implement additional adaptation, in any co-selected form (protection, retreat etc.). When reached thresholds correspond to unacceptable

conditions (red arrow in Fig. 10) an immediate plan should be put into action, considering the time needed for implementing the measures and the horizon for which the projection was made. This approach conforms to a climatic alarm system that can steer coastal adaptation, enabling a proactive approach to coastal protection that reduces risks and impacts with a low carbon footprint.

Conclusions

Restoring river-delta-coast systems can provide an enhanced delivery of ecosystem services and biodiversity gains, although such a restoration is not identical to an NbS or combination of NbS (Kerry et al. 2024). Restoring river-to-coast solid transport and natural coastal dynamics leads to a natural resilience under present and future climates, but the restoration actions present an important number of synergies and trade-offs that must be considered in any adaptation plan. Such a plan must define the starting and target deltas, which refer, respectively, to the co-selected (by all relevant stakeholders) initial or baseline deltaic state and to the consensus future delta with shared benefits for these stakeholders. Both deltaic states enable quantitative comparisons and an objective basis to co-define interventions and tipping points in spite of the possible challenges. From here, a prioritised list of actions with deadlines as a function of climatic and deltaic evolution can be defined and implemented. The dynamics of deltaic evolution illustrate one of the main challenges for sustainability, since decisions and governance become much easier for static settings, which, unfortunately, do not match highly dynamic deltaic systems. The Ebro River-coast continuum provides a test case to assess the performance of NbS, illustrating the limitations of conventional defence infrastructure for highly dynamic coastal fringes, where the co-existence of static infrastructure with an active coastal fringe result in undesired impacts, projected to increase under future climates, particularly due to accelerated relative sea level rise due to the cumulative effect of global warming and subsidence.

Restoration interventions require suitable techniques to speed up the restoration scales so that the delivered ecosystem services and biodiversity gains (improvements in coastal health associated with its natural structure and functions) can be perceived and shared along the whole coast and for communities and ecosystems in the lower river and receiving delta. Such techniques must build upon synergies to optimise the available sand and freshwater volumes, which are not enough to satisfy the demand for a traditional restoration under climate change. The same applies to the supporting funds, which although available, must always compete with alternative applications for other regions or sectors. Synergies in techniques and funding should be complemented by a clear governance strategy (Pernice et al. 2024) and supported by broad dissemination and communication activities, raising consensus on the type and scale of restoration interventions to be deployed.

Trade-offs, always resulting from restorations across domains and timescales, should also be explicitly addressed in the adaptation plan that sequences all river and coast restorations. Diverting scarce freshwater resources to nourish the downstream coast or enabling erosion in the catchment basin for the same purpose are trade-offs that must be inevitably faced. Dedicating a

continued funding for such restoration, including its upscaling and maintenance, should also be ensured, to build socioeconomic confidence on this type of solution for coastal protection. Any type of restoration, be it controlled river floods or coastal reshaping to achieve a higher roughness and local geodiversity, can also present environmental and economic trade-offs that should be considered in the overall assessment. NbS, such as controlled river discharges, vegetated dunes or wetland construction, produce benefits in terms of risk reduction (for erosion and flooding), improved water quality and productivity plus enhanced carbon sequestration (coastal blue carbon). These NbS may also produce environmental impacts, such as suspended sediment clouds or enhanced pollutant concentrations if there are contaminants in the mobilised sediments. Coastal roughness from embryo dunes or lagoons increase the resilience of the coastal fringe under wave and surge action, with smaller eroded volumes and more transient breaching. These results, derived from the performed numerical simulations and supported by the initial observations, lead to direct benefits in terms of durability of the supplied sediments (less erosion) and reduction of carbon footprint associated with longer spaced re-nourishments (longer duration of the supplied sand). This roughness, however, may hinder conventional sun-bathing activities, which prefer a flat and dry beach. The supportive governance, which, in many cases, requires a transformation from present structures, often fragmented and favouring short term criteria, must, thus, be supported by a pedagogic presentation of restoration benefits across scales and sectors.

Restoration interventions, here analysed for the Ebro Delta system, are also being carried out in other pilot cases within the Rest-Coast and twinned projects, which together address vulnerable freshwater and marine ecotones under climate change. From a coastal standpoint, restoration is being demonstrated for: a) seagrass beds in Arcachon Bay (Atlantic coast of SW France) and Foros Bay (Black Sea coast of Bulgaria); b) coastal wetlands in the Rhone Delta (France) and Venice lagoon (Italy); small scale lagoon and stream restorations in Sicily (Italy) and Nahal Dalia (Israel); c) artificial island in the Vistula Lagoon (Baltic coast of Poland); and d) the transboundary case of the Wadden Sea with a complex system of estuaries such as the Ems-Dollar (North Sea coasts of Germany and the Netherlands). All the pilot restorations present a wide range of challenges, which are benefitting from an explicit consideration of synergies (to enhance the restoration performance) and trade-offs (to avoid socioeconomic rejection). The technical, economic and social advances at each of the pilot restorations, are favouring an upscaling of such interventions, always underpinned by a supportive governance that favours the transition from conventional coastal protection to NbS interventions.

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Additional information

Conflict of interest

The authors have declared that no competing interests exist.

Ethical statement

No ethical statement was reported.

Use of AI

No use of AI was reported.

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Author contributions

Agustín Sánchez-Arcilla: Conceptualization, writing – original draft and writing – review and editing; Luis Garrote: Data curation, formal analysis, investigation, methodology; Vicente Gracia: Data curation, formal analysis, investigation, methodology; Iván Cáceres: Data curation, formal analysis, investigation, methodology; Xavier Sánchez-Artús: Data curation, formal analysis, investigation, methodology; Nuno Caiola: Data curation, formal analysis, investigation, methodology; Antoni Espanya: Supervision, validation, visualization; Manuel Espino: Data curation, formal analysis, investigation, methodology; Miguel Ángel Garcia: Supervision, validation, visualization; José María Grassa: Supervision, validation, visualization; Carles Ibáñez: Data curation, formal analysis, investigation, methodology; David López: Data curation, formal analysis, investigation, methodology; Marc Mestres: Data curation, formal analysis, investigation, methodology; José Manuel de la Peña: Data curation, formal analysis, investigation, methodology; Ernest Bladé: Data curation, formal analysis, investigation, methodology; Umberto Pernice: Conceptualization, methodology, Writing – original draft; Laura Puértolas: Conceptualization, methodology, Writing – original draft; David Santillan: Data curation, formal analysis, investigation, methodology; Shiri Zemah-Shamir: Data curation, formal analysis, investigation, methodology; Ana Iglesias: Data curation, formal analysis, investigation, methodology.

Author ORCIDs

Agustín Sánchez-Arcilla https://orcid.org/0000-0002-3450-6697
Luis Garrote https://orcid.org/0000-0001-9087-3638
Vicente Gracia https://orcid.org/0000-0002-4628-426X
Iván Cáceres https://orcid.org/0000-0002-7426-7029
Xavier Sánchez-Artús https://orcid.org/0000-0003-1478-1840
Nuno Caiola https://orcid.org/0000-0003-2692-2954
Manuel Espino https://orcid.org/0000-0002-9026-3976
Marc Mestres https://orcid.org/0000-0002-2010-8241
Ernest Bladé https://orcid.org/0000-0003-1770-3960
Umberto Pernice https://orcid.org/0000-0003-4206-4152
David Santillan https://orcid.org/0000-0002-9749-0522
Shiri Zemah-Shamir https://orcid.org/0000-0003-0651-0661
Ana Iglesias https://orcid.org/0000-0002-3183-6658

Data availability

All of the data that support the findings of this study are available in the main text.

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